(In)elastic Boosted Dark Matter Searches at DUNE

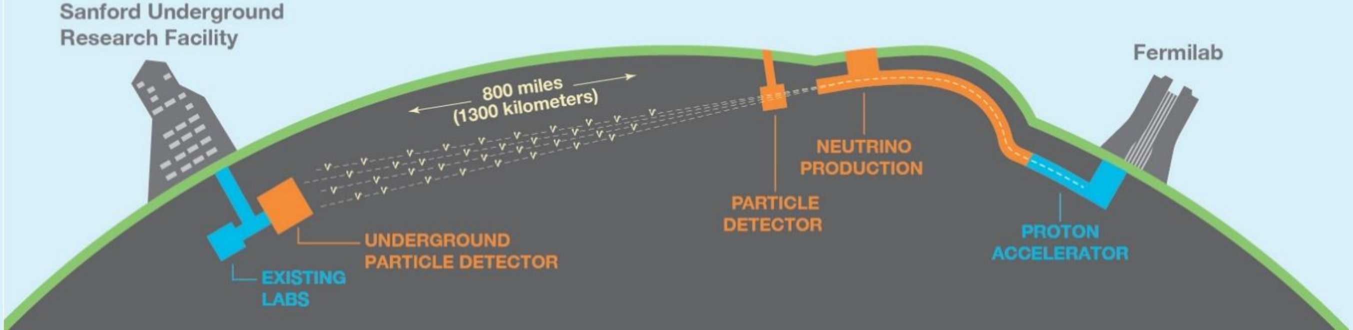
PRL 119 (2017) 161801, PLB 780 (2018) 543, 1803.03264, 1804.07302, more in progress,
in collaboration with H. Alhazmi, W. Bonivento, A. Chatterjee, A. De Roeck, K. Dienes, G. Giudice, K. Kong, P. Machado, Z. Moghaddam, J.-C. Park, S. Shin, B. Thomas, L. Whitehead, J. Yu

Doojin Kim

August 24th, 2018

Outline

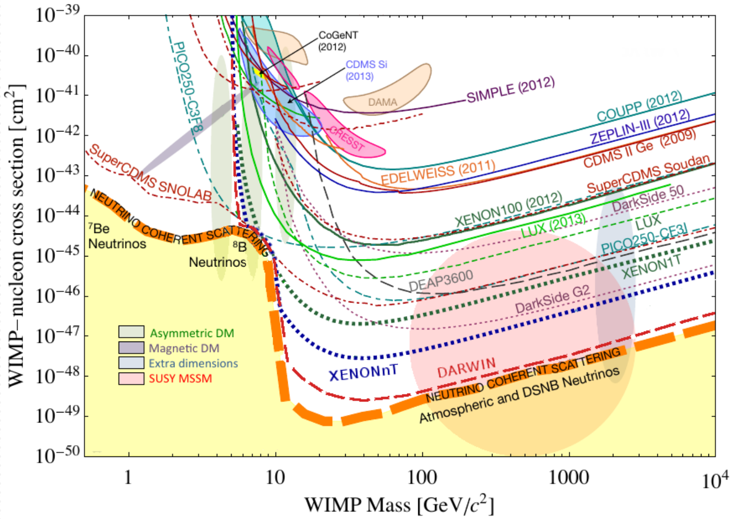
1. Physics Motivation
2. Signatures and General Strategies
3. Phenomenology: Experimental Sensitivities



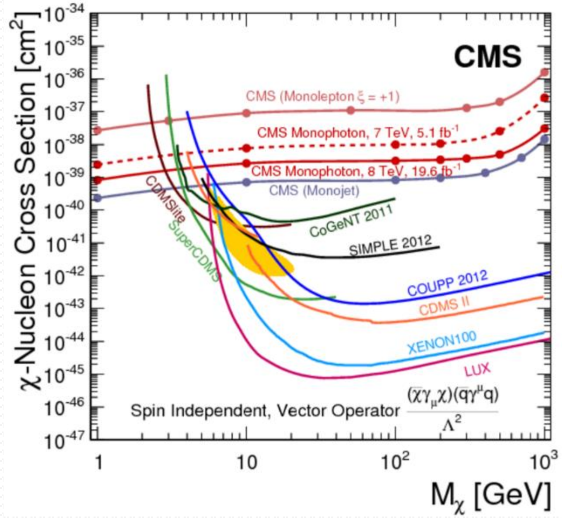
Physics Motivation

Current Status of DM Searches

- **No observation** of DM signatures via non-gravitational interactions (many searches/interpretations designed/performed under **WIMP/minimal dark-sector** scenarios) ⇒ merely excluding more parameter space in dark matter models



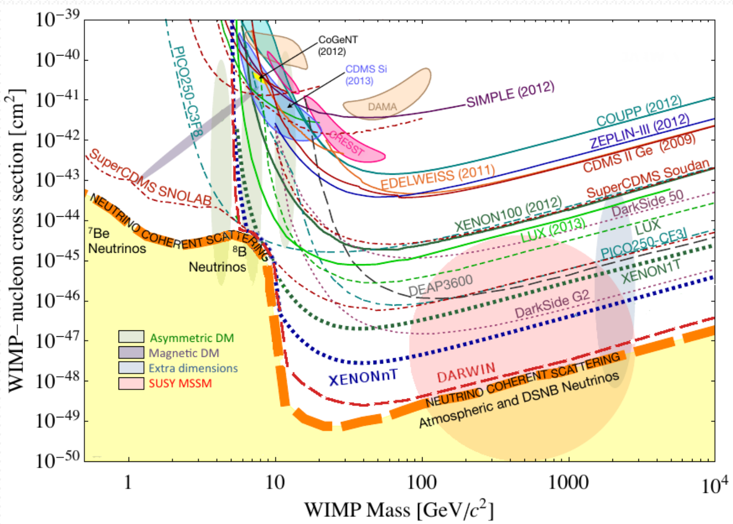
[P. Cushman, C. Calbiati and D. N. McKinsey, (2013); L. Baudis (2014)]



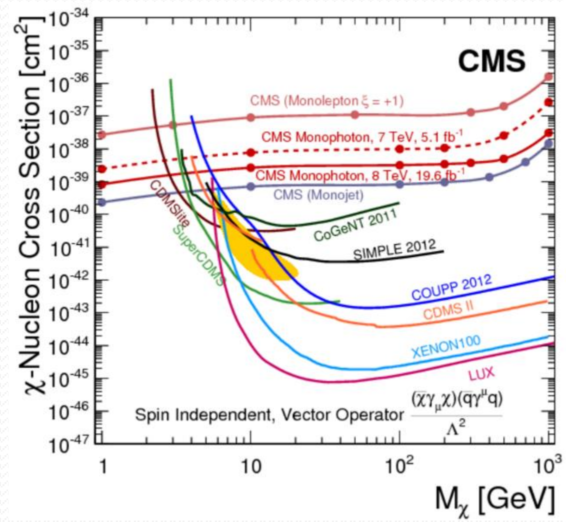
[CMS mono-photon search (2014)]

Current Status of DM Searches

- **No observation** of DM signatures via non-gravitational interactions (many searches/interpretations designed/performed under **WIMP/minimal dark-sector** scenarios) ⇒ merely excluding more parameter space in dark matter models



[P. Cushman, C. Calbiati and D. N. McKinsey, (2013); L. Baudis (2014)]



[CMS mono-photon search (2014)]

Time to change our approach?!

Conventional Approach

- Traditional approaches for DM searches:
  - ✓ Weak-scale mass
  - ✓ Weakly-coupled
  - ✓ Minimal dark sector
  - ✓ Elastic scattering
  - ✓ Non-relativistic

Conventional vs. Nonconventional Approach

- Traditional approaches for DM searches:
  - ✓ ~~Weak-scale~~ mass
  - ✓ ~~Weakly-coupled~~
  - ✓ ~~Minimal~~ dark sector
  - ✓ ~~Elastic scattering~~
  - ✓ ~~Non-relativistic~~

- Modified approaches for DM searches:
  - ✓ Other mass scale: e.g., PeV, sub-GeV, MeV, keV, meV, …
  - ✓ Weaker coupling to the SM: e.g., vector portal (dark photon), scalar portal, axion portal, …
  - ✓ "Flavorful" dark sector: e.g., more dark matter species, unstable heavier dark sector states, …
  - ✓ Inelastic scattering (i.e., up-scatter to an "excited" state)
  - ✓ Relativistic

Conventional vs. Nonconventional Approach

- Traditional approaches for DM searches:
  - ✓ ~~Weak-scale~~ mass
  - ✓ ~~Weakly-coupled~~
  - ✓ ~~Minimal dark~~ sector
  - ✓ ~~Elastic scattering~~
  - ✓ ~~Non-relativistic~~

- Modified approaches for DM searches:
  - ✓ Other mass scale: e.g., PeV, sub-GeV, MeV, keV, meV, …
  - ✓ Weaker coupling to the SM: e.g., vector portal (dark photon), scalar portal, axion portal, …
  - ✓ "Flavorful" dark sector: e.g., more dark matter species, unstable heavier dark sector states, …
  - ✓ Inelastic scattering (i.e., up-scatter to an "excited" state)
  - ✓ Relativistic

DM Search Strategies

Scattering \ v_{DM}	Non-relativistic ($v_{DM} \ll c$)
elastic	Direct detection
*in*elastic	inelastic DM (iDM)

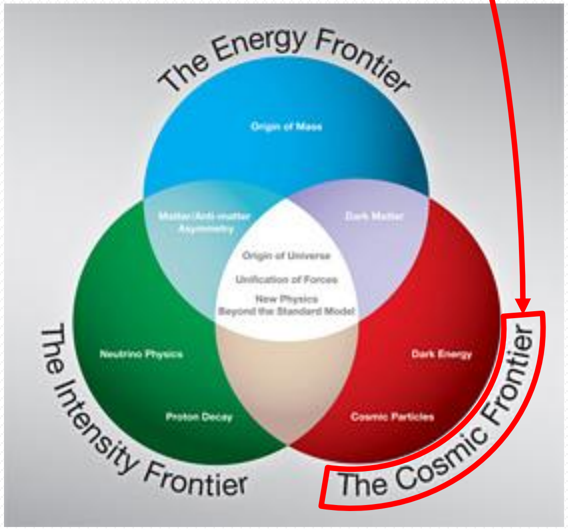
Very well-studied

DM Search Strategies

Scattering \ v_{DM}	Non-relativistic ($v_{DM} \ll c$)	Relativistic ($v_{DM} \sim c$)
elastic	Direct detection	Boosted DM (eBDM)
*in*elastic	inelastic DM (iDM)	inelastic BDM (iBDM)

DM Search Strategies

v_{DM} / Scattering	Non-relativistic ($v_{DM} \ll c$)	Relativistic ($v_{DM} \sim c$)
elastic	Direct detection	Boosted DM (eBDM)
*in*elastic	inelastic DM (iDM)	inelastic BDM (iBDM)

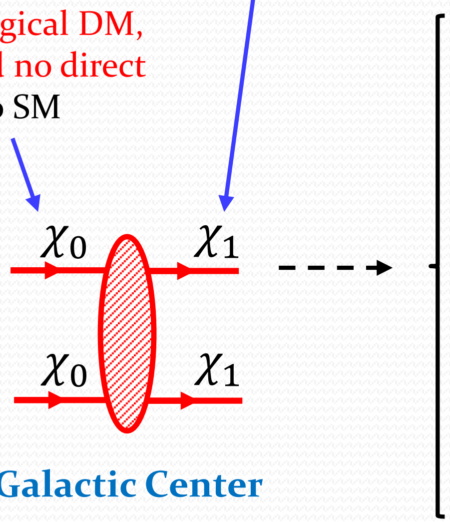


Signatures and General Strategies

Generic Boosted Dark Matter (BDM) Event Topologies

$m_0 = E_1 = \sim 30$ MeV $- \sim 20$ GeV
with $\mathcal{F}_{\chi_1} = \sim 10^{-1} - 10^{-7}$ cm^{-2}s^{-1}

Cosmological DM, Assumed no direct couple to SM



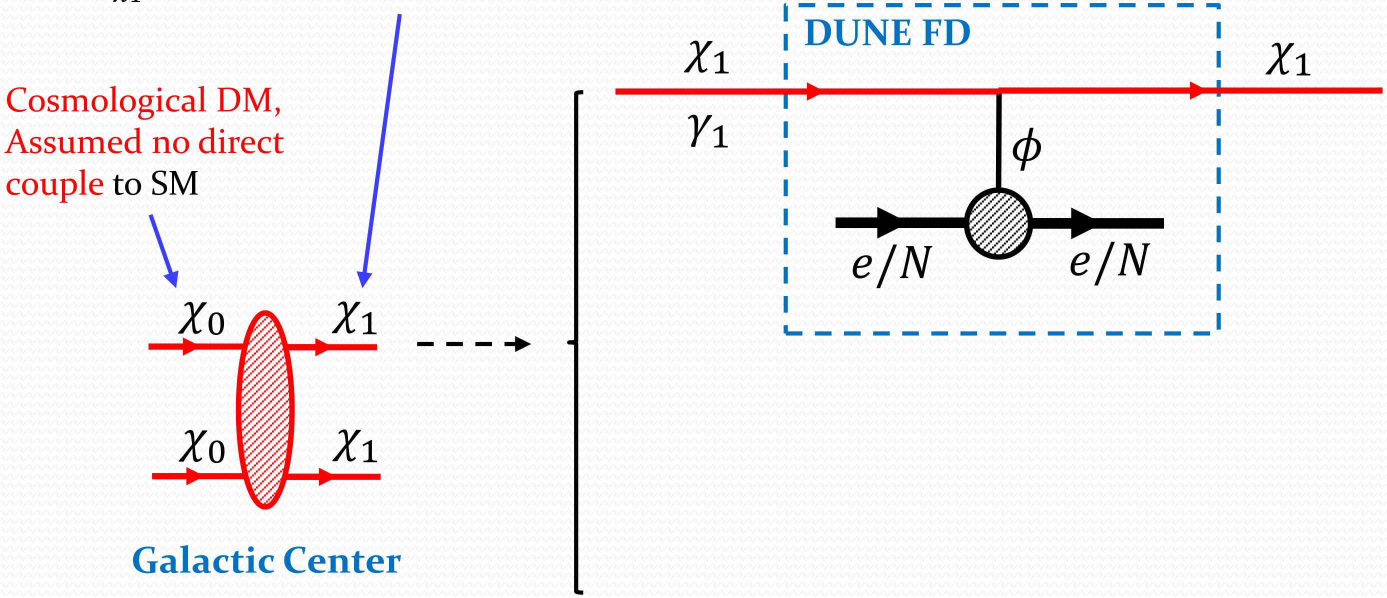
Galactic Center

- χ_0: heavier DM
- χ_1: lighter DM
- γ_1: boost factor of χ_1
- χ_2: massive unstable dark-sector state
- ϕ: mediator/portal particle

Generic Boosted Dark Matter (BDM) Event Topologies

$m_0 = E_1 = \sim 30$ MeV $- \sim 20$ GeV
with $\mathcal{F}_{\chi_1} = \sim 10^{-1} - 10^{-7}$ cm^{-2}s^{-1}

(a) Elastic scattering (eBDM) at DUNE [Necib, Moon, Wongjirad, Conrad (2016); Alhazmi, Kong, Mohlabeng, Park (2016)] (and at ProtoDUNE [**DK**, Kong, Park, Shin (2018)])

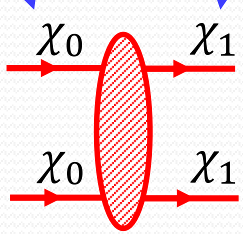


- χ_0: heavier DM
- χ_1: lighter DM
- γ_1: boost factor of χ_1
- χ_2: massive unstable dark-sector state
- ϕ: mediator/portal particle

Generic Boosted Dark Matter (BDM) Event Topologies

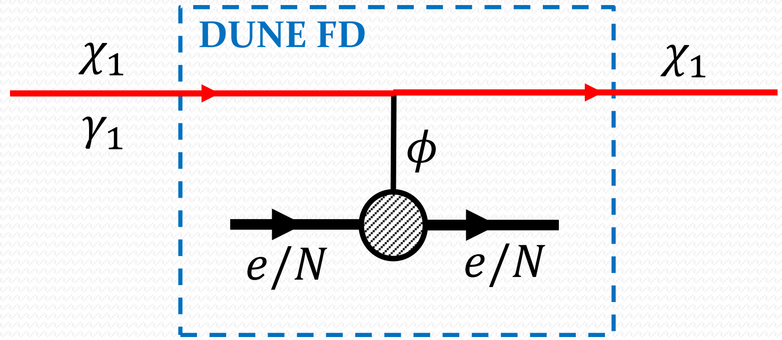
$m_0 = E_1 = \sim 30\ \text{MeV} - \sim 20\ \text{GeV}$
with $\mathcal{F}_{\chi_1} = \sim 10^{-1} - 10^{-7}\ \text{cm}^{-2}\text{s}^{-1}$

Cosmological DM, Assumed no direct couple to SM

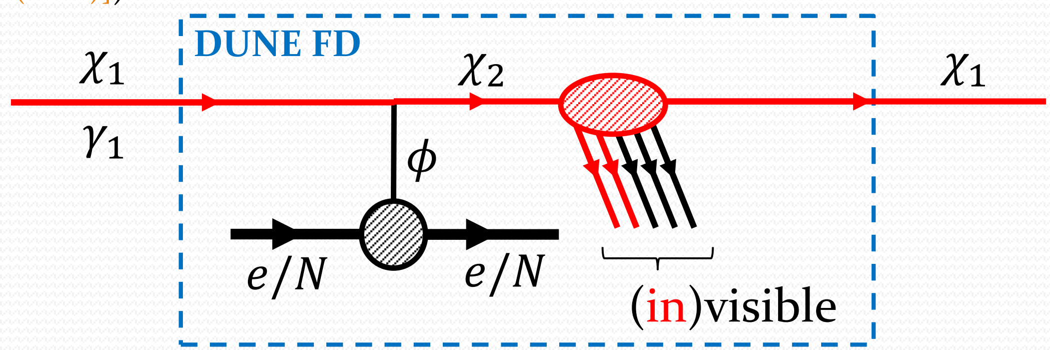


Galactic Center

(a) Elastic scattering (eBDM) at DUNE [Necib, Moon, Wongjirad, Conrad (2016); Alhazmi, Kong, Mohlabeng, Park (2016)] (and at ProtoDUNE [**DK**, Kong, Park, Shin (2018)])



(b) Inelastic scattering (iBDM) at DUNE [**DK**, Park, Shin (2016)] (and at ProtoDUNE [Chatterjee, De Roeck, **DK**, Moghaddam, Park, Shin, Whitehead, Yu (2018)])

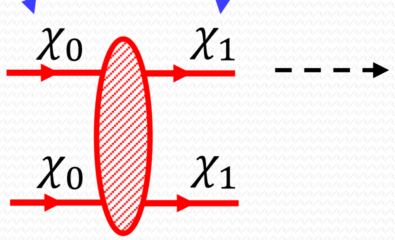


- χ_0: heavier DM
- χ_1: lighter DM
- γ_1: boost factor of χ_1
- χ_2: massive unstable dark-sector state
- ϕ: mediator/portal particle

Generic Boosted Dark Matter (BDM) Event Topologies

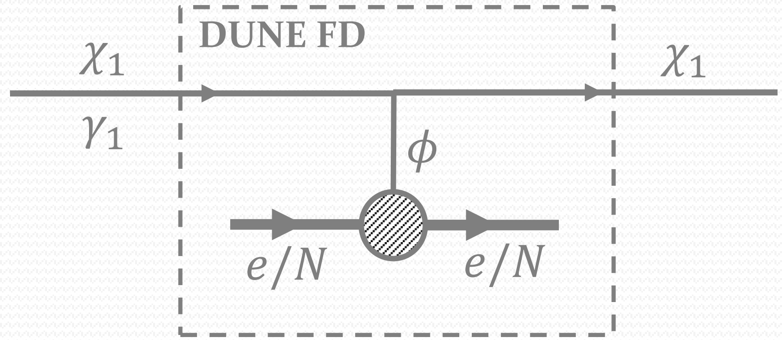
$m_0 = E_1 = \sim 30$ MeV $- \sim 20$ GeV
with $\mathcal{F}_{\chi_1} = \sim 10^{-1} - 10^{-7}$ cm^{-2}s^{-1}

Cosmological DM,
Assumed no direct
couple to SM

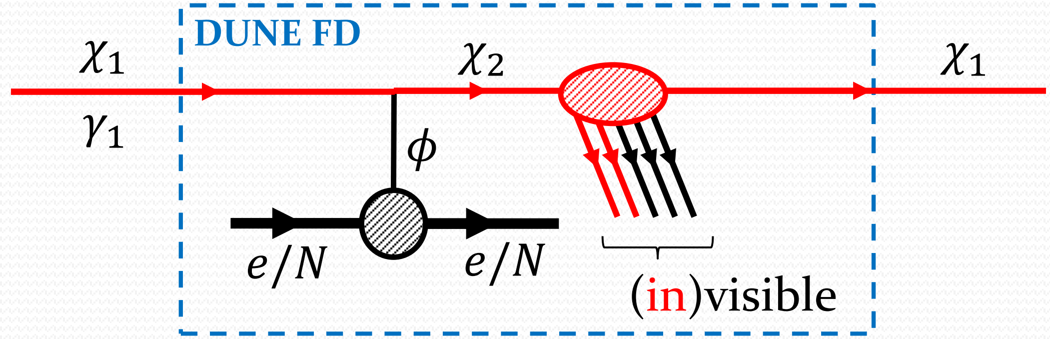


Galactic Center

(a) Elastic scattering (eBDM) at DUNE [Necib, Moon, Wongjirad, Conrad (2016); Alhazmi, Kong, Mohlabeng, Park (2016)] (and at ProtoDUNE [**DK**, Kong, Park, Shin (2018)])

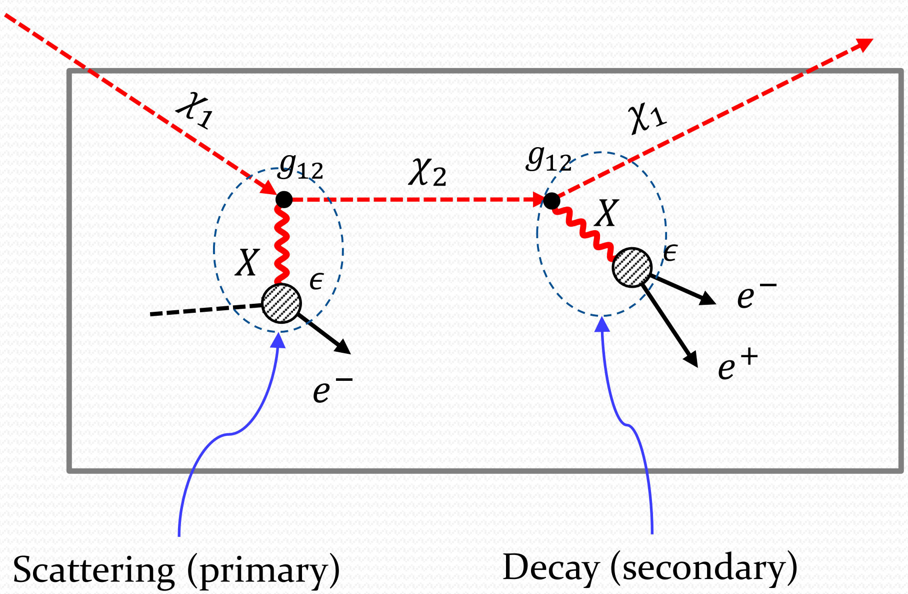


(b) Inelastic scattering (iBDM) at DUNE [**DK**, Park, Shin (2016)] (and at ProtoDUNE [Chatterjee, De Roeck, **DK**, Moghaddam, Park, Shin, Whitehead, Yu (2018)])



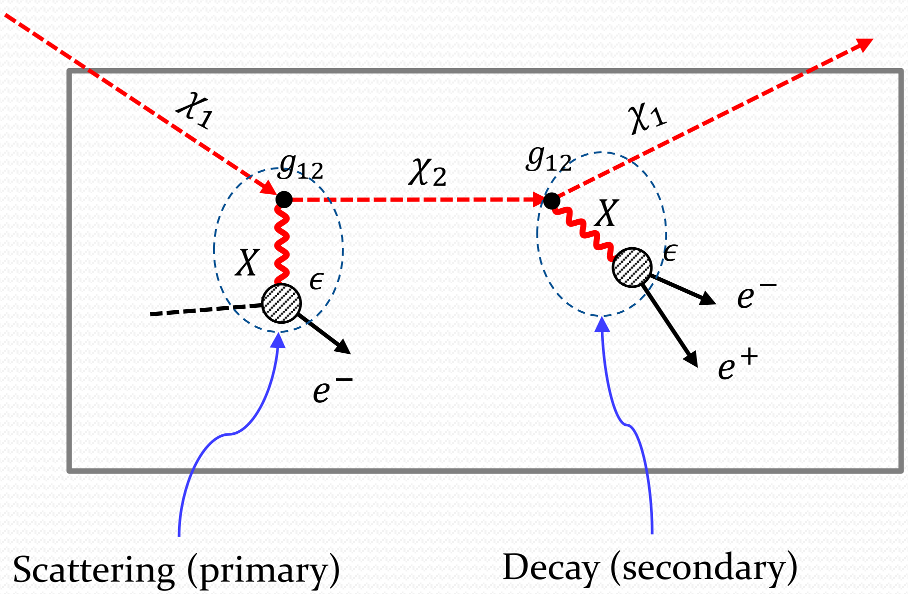
- χ_0: heavier DM
- χ_1: lighter DM
- γ_1: boost factor of χ_1
- χ_2: massive unstable dark-sector state
- ϕ: mediator/portal particle

Expected Signatures with a Dark Photon Scenario



- Benchmark model to describe interactions between dark-sector and SM-sector particles: dark photon (X) model.
- $m_2 > m_1 + 2m_e$
- **Three electron tracks** with two possibilities
  - ✓ "Prompt" *i*BDM: scattering (primary) and decay (secondary) arise at the same point.
  - ✓ "Displaced" *i*BDM: primary and secondary interaction points appear displaced (often due to long-lived χ_2)

Expected Signatures with a Dark Photon Scenario

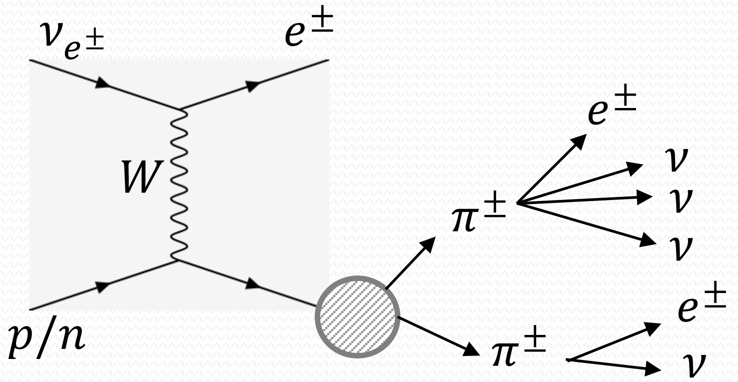


- ❑ Benchmark model to describe interactions between dark-sector and SM-sector particles: dark photon (X) model.
- ❑ $m_2 > m_1 + 2m_e$
- ❑ **Three electron tracks** with two possibilities
  - ✓ "Prompt" *i*BDM: scattering (primary) and decay (secondary) arise at the same point.
  - ✓ "Displaced" *i*BDM: primary and secondary interaction points appear displaced (often due to long-lived χ_2)

- ❑ Note that **tracks will pop up inside the fiducial volume**.
- ❑ Straightforwardly applicable to proton recoil (up to form factor, DIS etc.)

Expected Number of ν-induced Events

- Atm.-ν may induce multi-track events (which could be backgrounds)
- The dominant source
  - ✓ **ν_e-induced C.C.** events

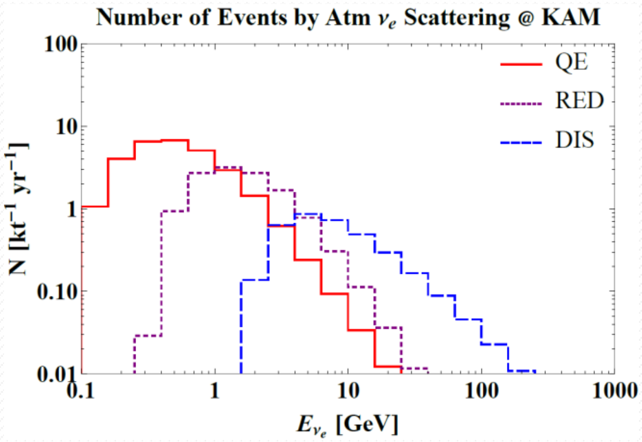


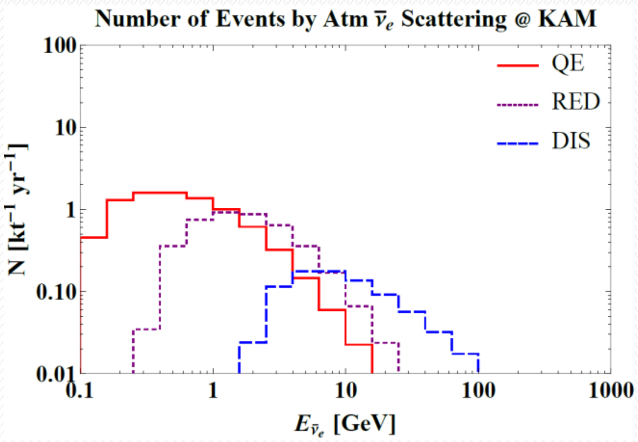
e.g. $\pi^\pm \to \mu^\pm\nu \to e^\pm\nu\nu\nu$, $\pi^\pm \to e^\pm\nu$

- Other subdominant sources
  - ✓ N.C. events: smaller cross section
  - ✓ ν_τ-induced: too small flux, hence negligible
  - ✓ ν_μ-induced C.C.: leaving an energetic (primary) muon (which can be tagged easily)

Expected Number of ν-induced Events

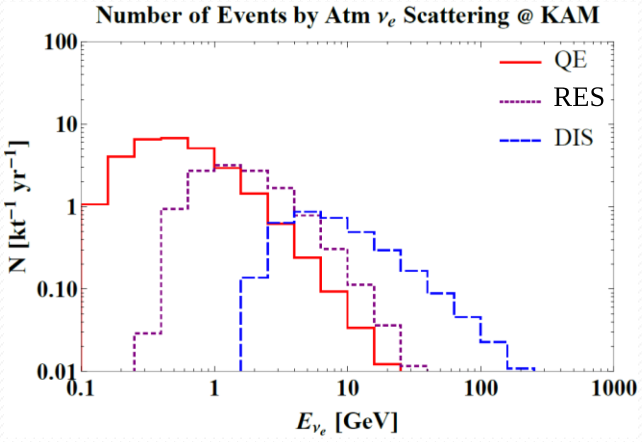
- ν_e-flux [SK Collaboration, 1502.03916] $\otimes$ ν_e-cross section [Formaggio, Zeller, 1305.7513]

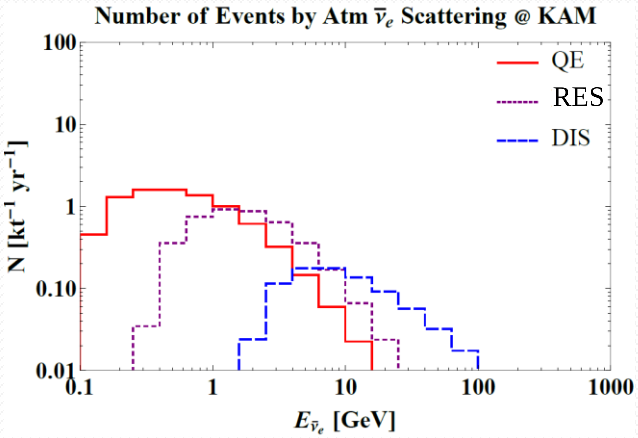




Expected Number of ν-induced Events

- ❑ ν_e-flux [SK Collaboration, 1502.03916] ⊗ ν_e-cross section [Formaggio, Zeller, 1305.7513]





- ❑ Most DIS events result in messy final states, not mimicking signal events, while a majority of resonance events may create a few mesons in the final state [Formaggio, Zeller, 1305.7513].
  - ⇒ **12.2** events/kt/yr are potentially relevant, i.e., **240 (480)** events for **20 kt (40 kt)**
- ❑ (quality) track-based particle identification, timing information etc at DUNE LArTPC detectors can suppress such events significantly. → **Zero BG is achievable**!

Other Experimental Challenges

- For a given set of m_1, γ_1, and m_T, the maximum accessible m_2 is

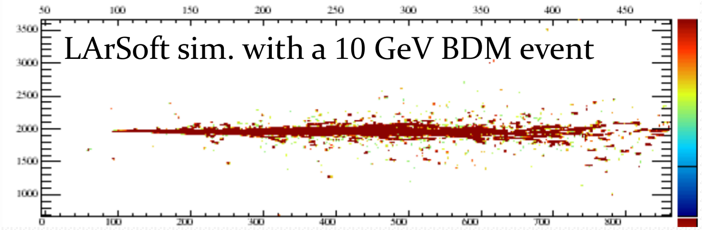
$$m_2 \leq \sqrt{m_T^2 + 2\gamma_1 m_1 m_T + m_1^2} - m_T,$$

- and if the target is relatively light ($m_1 \gg m_T$), which is the case of e-scattering, we find

$$m_2 \lesssim m_1 + \gamma_1 m_e.$$

$\Rightarrow$ A large γ_1 is preferred to access the heavier dark-sector state.

$\Rightarrow$ All final state particles are likely to be highly collimated.



Other Experimental Challenges

- For a given set of m_1, γ_1, and m_T, the maximum accessible m_2 is

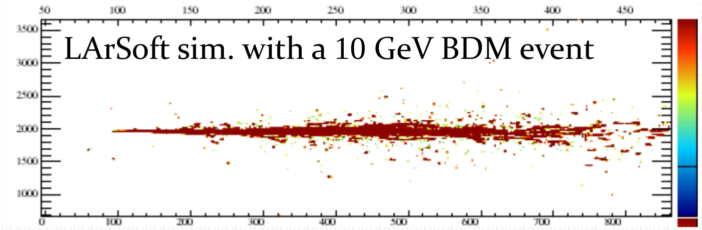
$$m_2 \leq \sqrt{m_T^2 + 2\gamma_1 m_1 m_T + m_1^2} - m_T,$$

- and if the target is relatively light ($m_1 \gg m_T$), which is the case of e-scattering, we find

$$m_2 \lesssim m_1 + \gamma_1 m_e.$$

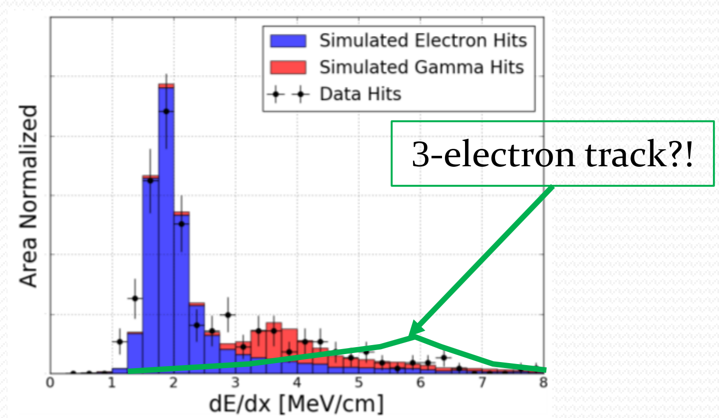
$\Rightarrow$ A large γ_1 is preferred to access the heavier dark-sector state.

$\Rightarrow$ All final state particles are likely to be highly collimated.



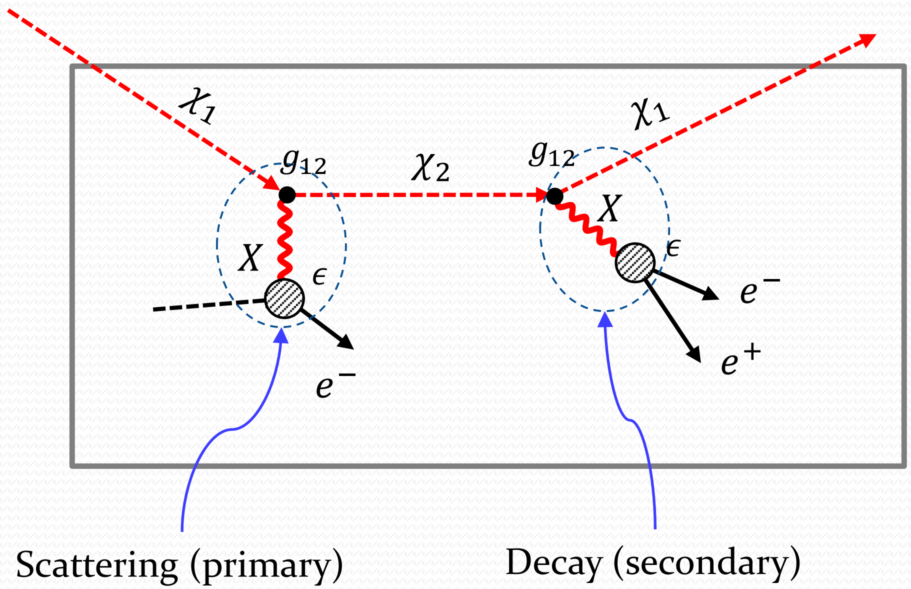
- General expectation: **great angular and position resolutions** at DUNE!

$\Rightarrow$ dE/dx in totally overlaid track vs. photon track vs. electron track [De Roeck, **DK**, Moghaddam, Park, Shin, Whitehead, in progress]



Phenomenology: Experimental Sensitivities

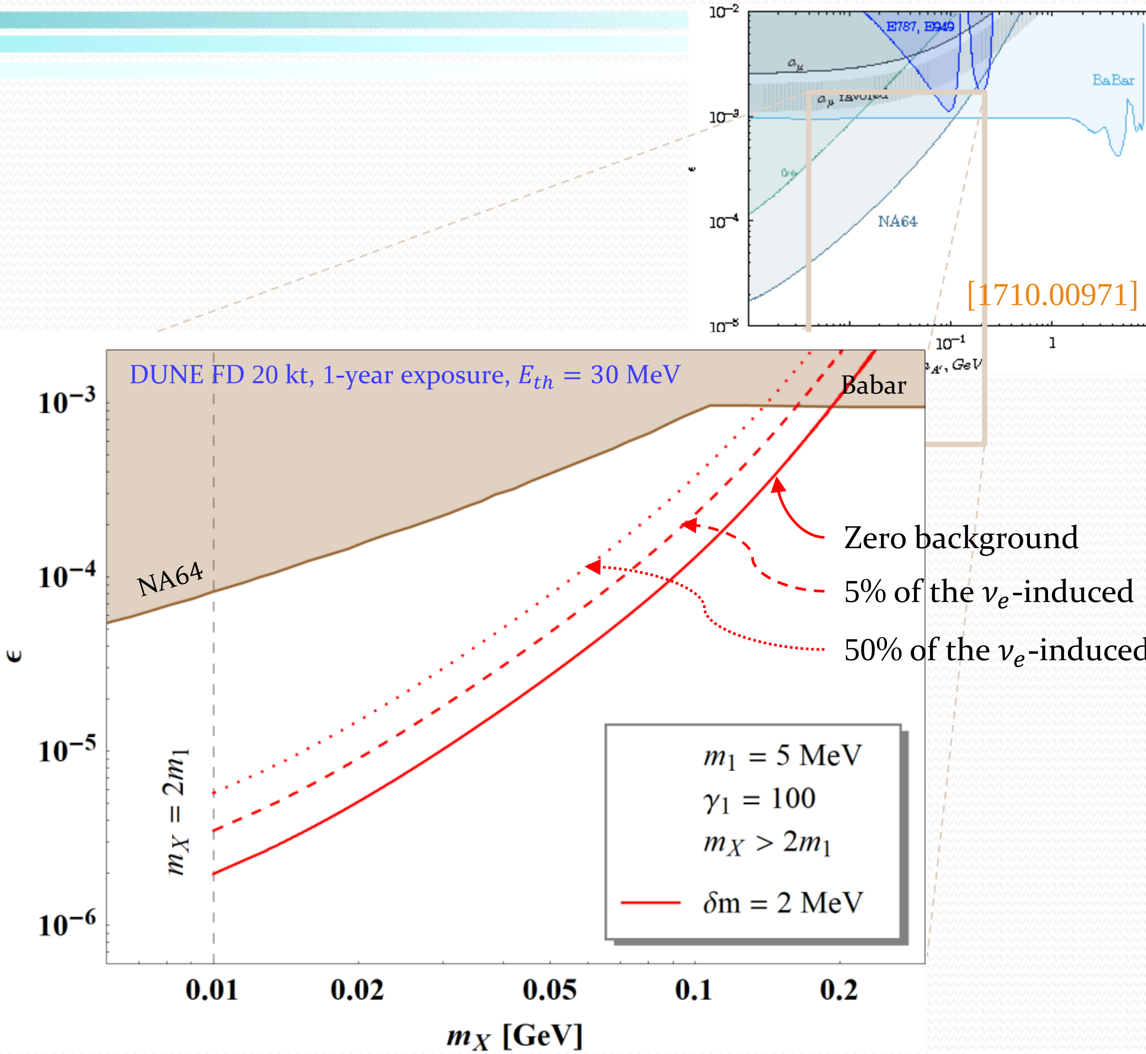
Reminder for the Signal of Interest



- ❑ Remember that dark photon is a "player" in the benchmark model, allowing us to study phenomenology of dark photon!

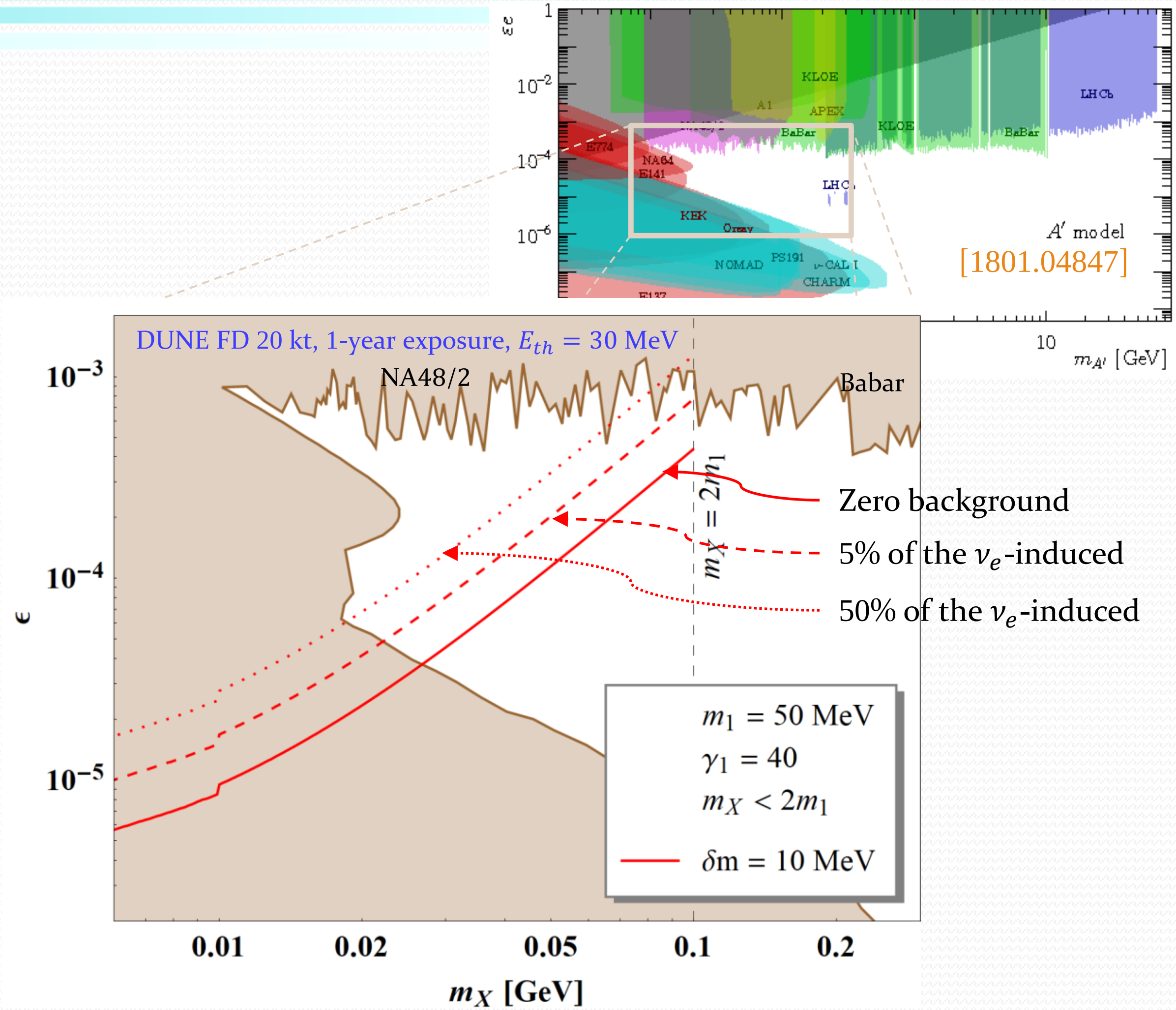
Dark Photon Parameter Space: Invisible X Decay

- Case study 1: mass spectra for which dark photon decays into DM pairs, i.e., $m_X > 2m_1$
- 1-year data collection from the entire sky, $g_{12} = 1$, $E_{th} = 30$ MeV and various BGs are assumed.
- Even in the worst scenario (poor BG rejection, i.e., dotted curve) unexplored parameter space can be probed by DUNE.



Dark Photon Parameter Space: Visible X decay

- ❑ Case study 2: mass spectra for which dark photon decays into lepton pairs, i.e., $m_X < 2m_1$
- ❑ 1-year data collection from the entire sky, $g_{12} = 1$, $E_{th} = 30$ MeV and various BGs are assumed.



Model-independent Reach

- **Non-trivial** to find appropriate parameterizations for providing **model-independent reaches** due to many parameters involved in the model
- Number of signal events $N_{\rm sig}$ is

$$N_{\rm sig} = \sigma_\epsilon \cdot \mathcal{F} \cdot A \cdot t_{\rm exp} \cdot N_e$$

  - σ_ϵ: scattering cross section between χ_1 and (target) electron
  - $\mathcal{F}$: flux of incoming (boosted) χ_1
  - A: acceptance
  - $t_{\rm exp}$: exposure time
  - N_e: total # of target electrons

Controllable! (once a detector is determined)

Here we factored out the acceptance related to distance between the primary (ER) and the secondary vertices, other factors like cuts, energy threshold, etc are absorbed into σ_ϵ.

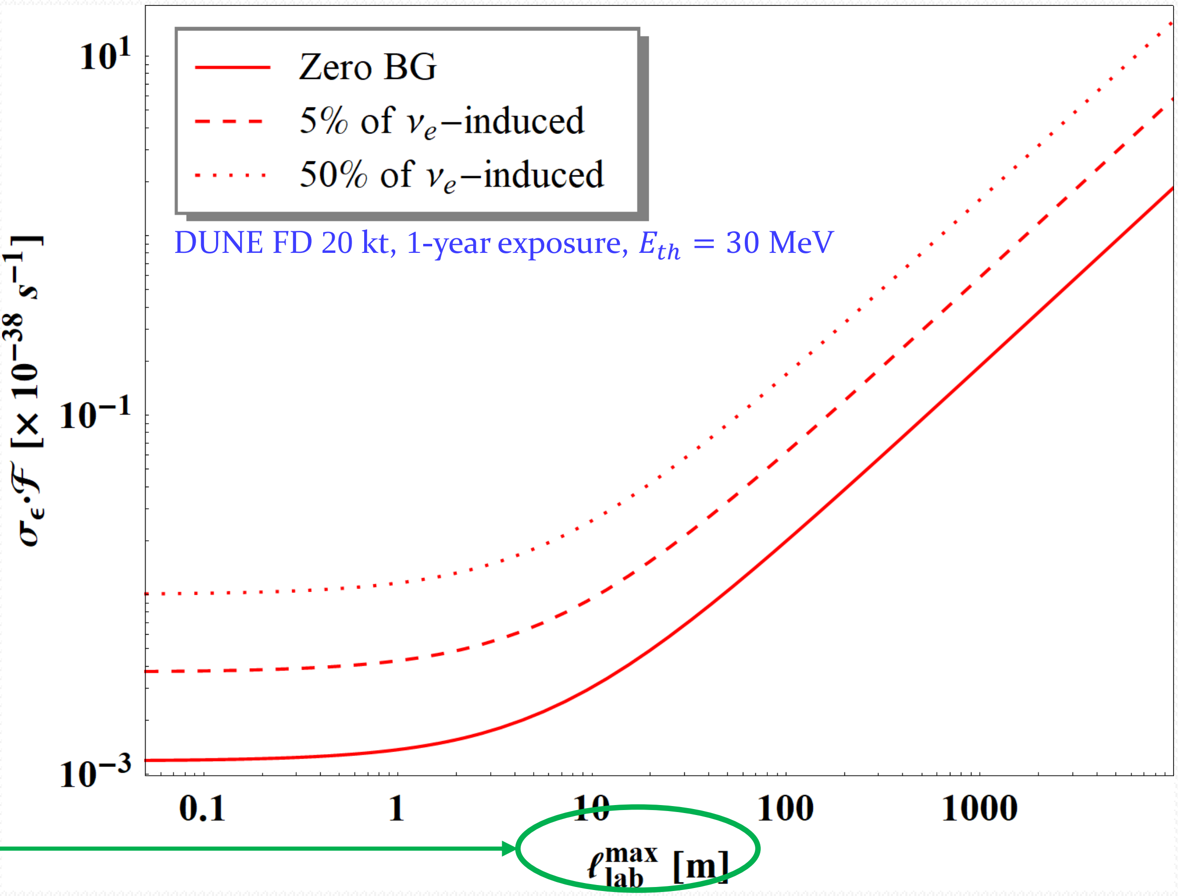
Model-independent Reach: Prospect

90% C.L. with various BGs

$$\sigma_\epsilon \cdot \mathcal{F} \geq \frac{N^{90}}{A(\ell_{\rm lab}) \cdot \underbrace{t_{\rm exp} \cdot N_e}_{\text{Calculable}}}$$

Evaluated under the assumption of cumulatively isotropic χ_1 flux

$\ell_{\rm lab}$ different event-by-event, so taking $\ell_{\rm lab}^{\rm max}$ for more conservative limit



Model-independent Reach: More Familiar Form

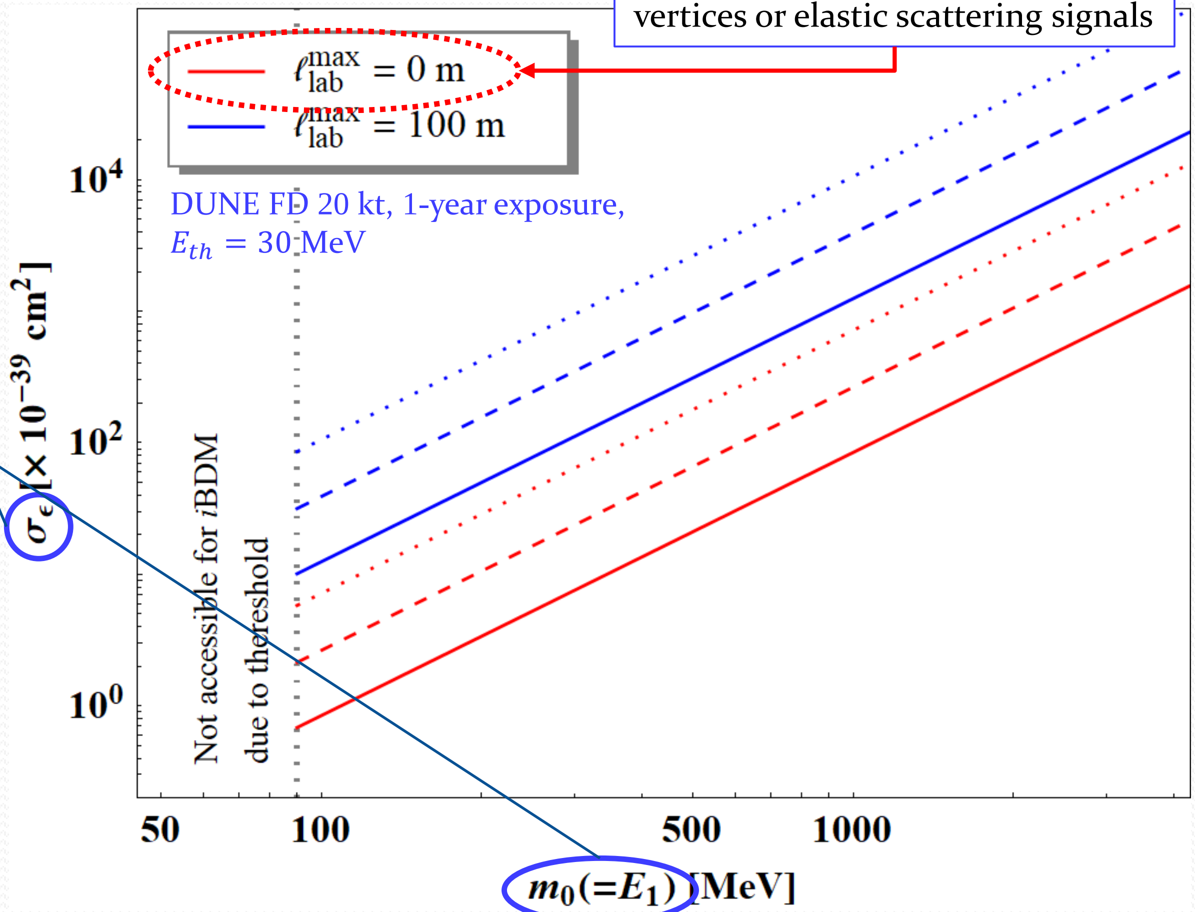
$$\sigma_\epsilon \geq \frac{N^{90}}{\mathcal{F}\cdot A\cdot t_{\rm exp}\cdot N_e}$$

$$\mathcal{F} \sim \frac{\langle \sigma v\rangle_{\chi_0\chi_0\to\chi_1\chi_1}}{m_0^2}$$

$\Rightarrow$ Experimental sensitivity can be represented by σ_ϵ vs. $E_1 (= m_0 = \gamma_1 m_1)$

(cf. σ vs. $m_{\rm DM}$ in conventional WIMP searches)

relevant to signals with overlaid vertices or elastic scattering signals



Conclusions and Outlook

Scattering \ v_{DM}	Non-relativistic ($v_{DM} \ll c$)	Relativistic ($v_{DM} \sim c$)
elastic	Direct detection	Boosted DM (eBDM)
*in*elastic	inelastic DM (iDM)	**inelastic BDM (*i*BDM)**

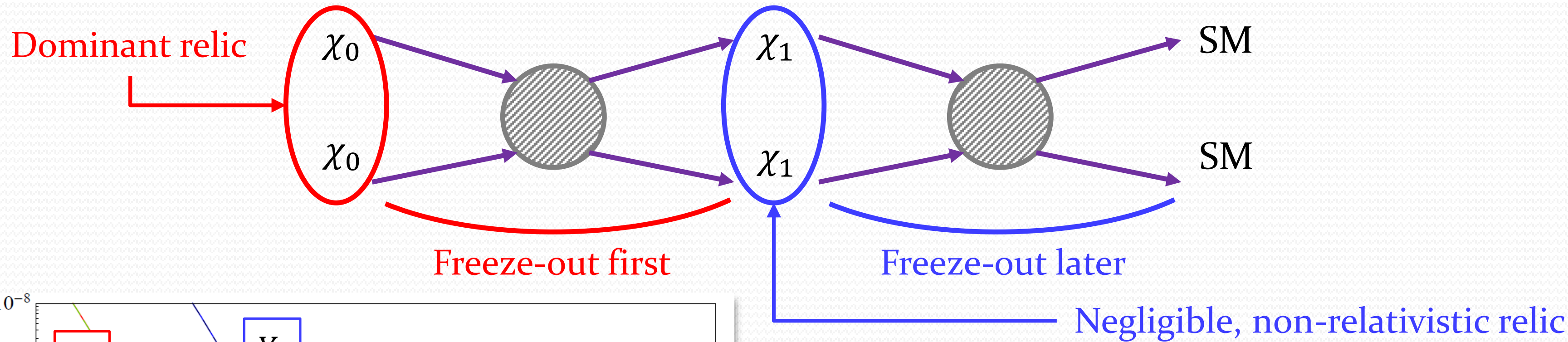
- The boosted (light) DM search is **promising** and provides a **new direction** to study DM phenomenology.
- Theoretical/phenomenological studies have been actively conducted and in progress.
- These ideas can be tested in the **DUNE experiment**.
  - ✓ Experimental studies at LArTPC detectors have already begun, e.g. ProtoDUNE, ICARUS T600 (using actual data taken at Gran Sasso)

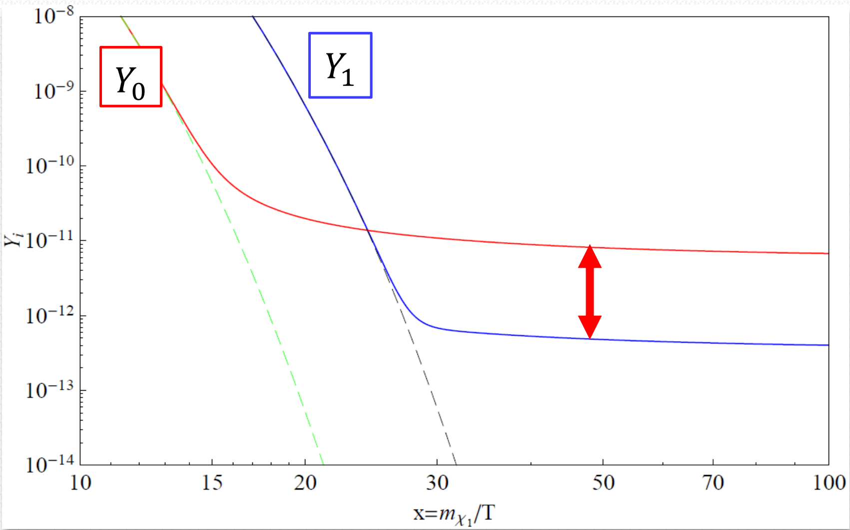
thank you !

Back-up

Two-component Boosted DM Scenario

- A possible relativistic source: BDM scenario (cosmic frontier), stability of the two DM species ensured by separate symmetries, e.g., $Z_2 \otimes Z_2'$, $U(1) \otimes U(1)'$, etc.

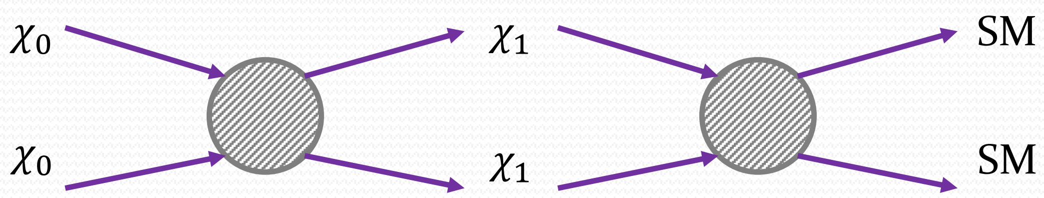




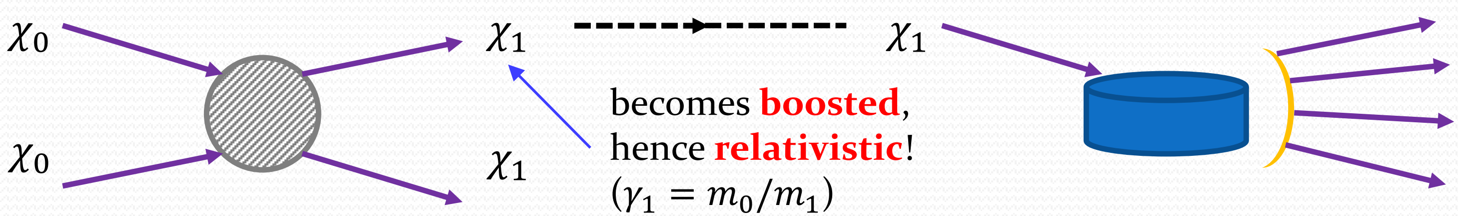
<u>"Assisted" freeze-out</u> mechanism

[Belanger, Park (2011)]

“Relativistic” Dark Matter Search



- ✓ Heavier relic χ_0: hard to detect it due to tiny/negligible coupling to SM
- ✓ Lighter relic χ_1: hard to detect it due to small amount



(Galactic Center at **CURRENT** universe)

(Laboratory)

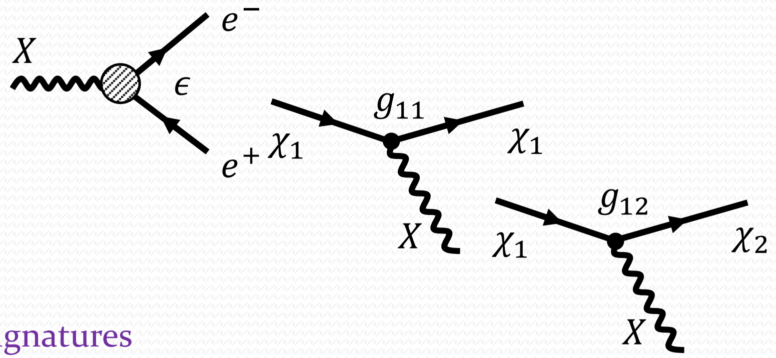
[Agashe, Cui, Necib, Thaler (2014)]

Production of BDM & Benchmark Model

- Production of boosted DM at the universe: two-component boosted DM scenario [Agashe, Cui, Necib, Thaler (2014)]

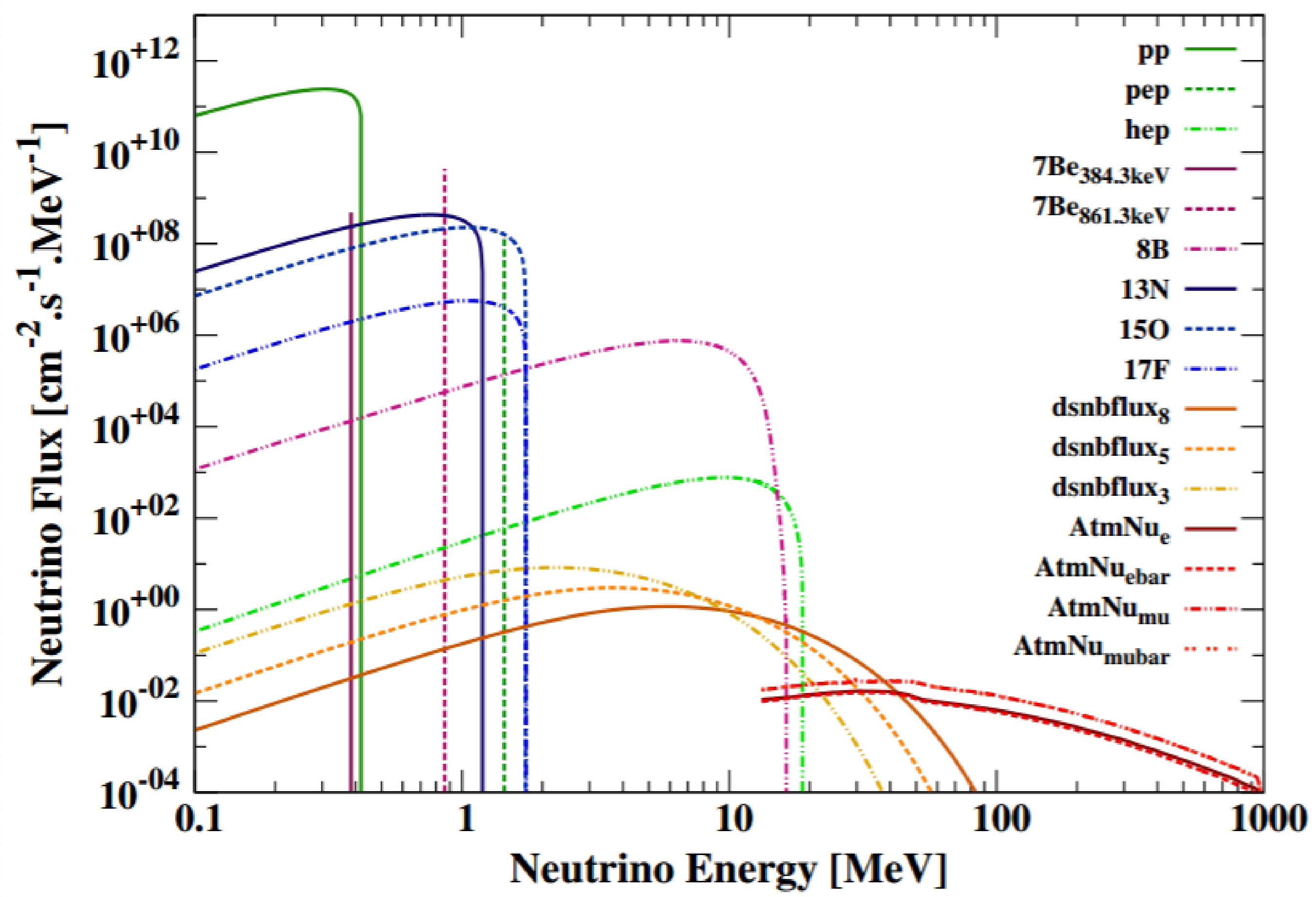
$$\mathcal{L}_{\rm int} \ni -\frac{\epsilon}{2} F_{\mu\nu}X^{\mu\nu} + g_{11}\bar{\chi}_1\gamma^\mu\chi_1 X_\mu + g_{12}\bar{\chi}_2\gamma^\mu\chi_1 X_\mu + \text{h.c.} + (\text{others})$$

- Vector portal (e.g., dark gauge boson scenario) [Holdom (1986)]
- Fermionic DM
  - χ_2: a heavier (unstable) dark-sector state
  - Flavor-conserving neutral current $\Rightarrow$ elastic scattering
  - Flavor-changing neutral current $\Rightarrow$ inelastic scattering



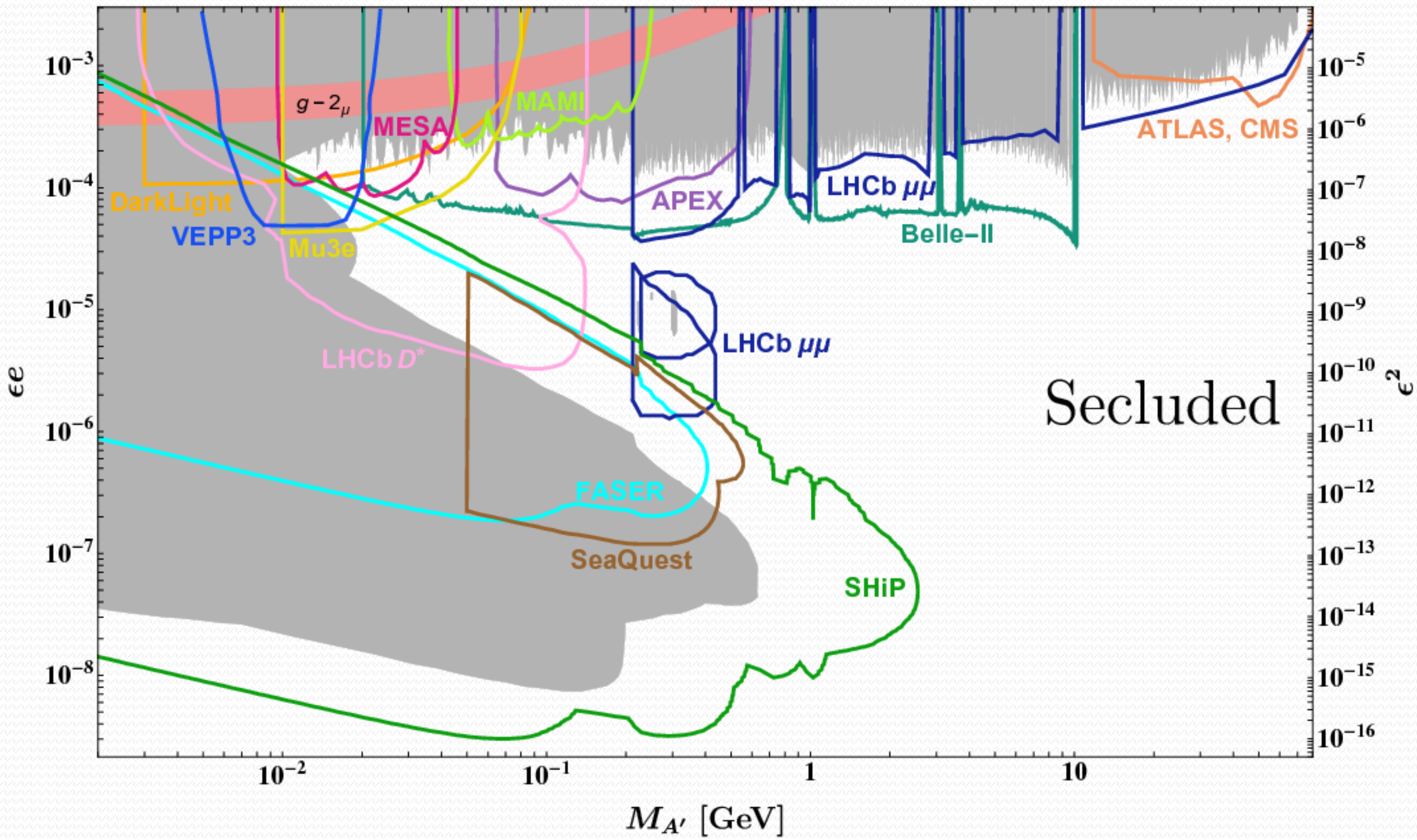
- Not restricted to this model: various models conceiving BDM signatures
  - BDM source: galactic center, solar capture, dwarf galaxies, assisted freeze-out, semi-annihilation, fast-moving DM etc. [Agashe et al. (2014); Berger et al. (2015); Kong et al. (2015); Alhazmi et al. (2017); Super-K (2017); Belanger et al. (2011); D'Eramo et al. (2010); Huang et al. (2013)]
  - Portal: vector portal, scalar portal, etc.
  - DM spin: fermionic DM, scalar DM, etc.
  - iBDM-inducing operator: two chiral fermions, two real scalars, dipole moment interactions, etc. [Tucker-Smith, Weiner (2001); Giudice, **DK**, Park, Shin (2017)]

Neutrino Fluxes



[Ruppin et al., (2014)]

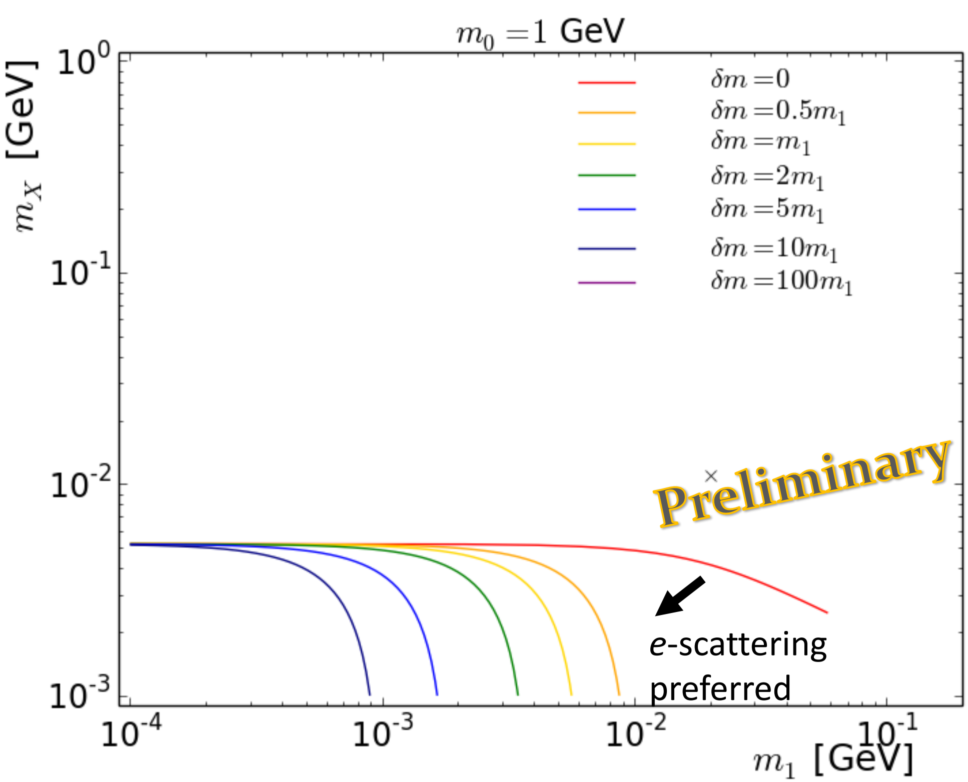
Prospective Parameter Reaches for Visibly Decaying Dark Photon



[Bauer, Foldenauer, Jaeckel (2018)]

e-scattering vs. *p*-scattering

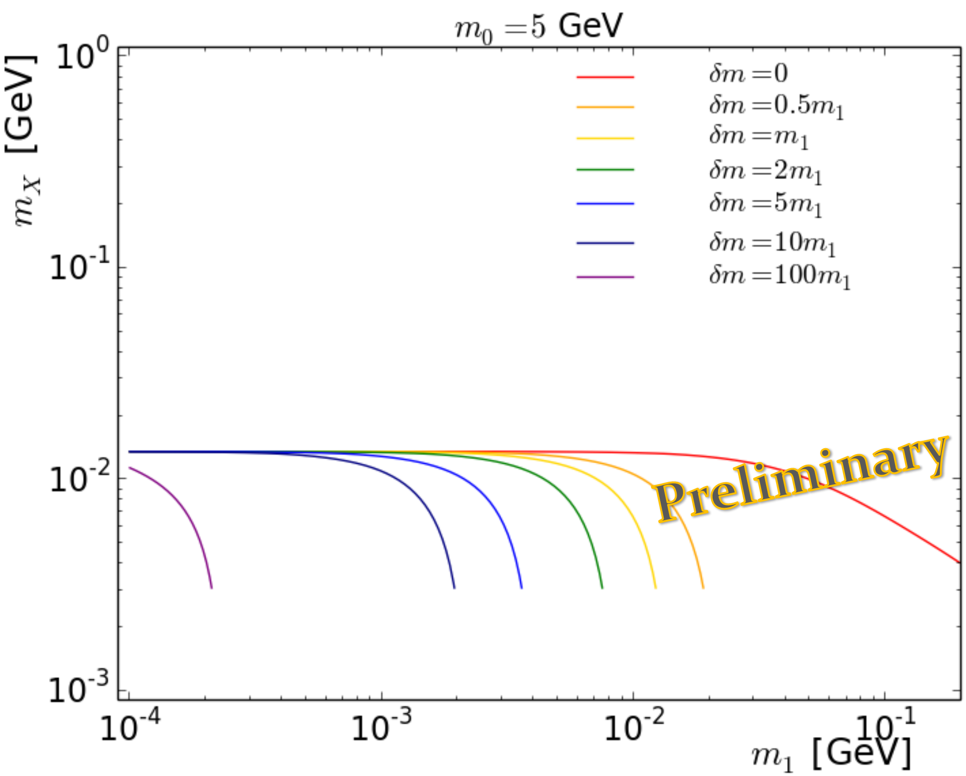
❑ Comparison of cross sections via *e*-scattering and *p*-scattering



❑ As m_X becomes negligible, *e*-scattering is more advantageous than *p*-scattering. ⇐ smaller suppression by the mass of target electron.

❑ "More" inelastic scattering shrinks the *e*-scattering preferred region. ⇐ *p*-scattering is better at accessing heavier dark sector states.

e-scattering vs. p-scattering



- As m_0 becomes large, the e-scattering preferred region expands. $\Leftarrow$ Difficulty in accessing heavier dark-sector states via e-scattering is relaxed by a larger boost factor of χ_1.